Unleashing Photosynthesis and Nitrogen Fixation for Carbon Neutral Production of N-Rich Compounds

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Reliance on nitrogen fertilizers continues to grow as food production strives to keep pace with a fast-growing world population. Currently, synthetic NH_3 constitutes the heart of the fertilizer industry. The Haber-Bosch process is the principal source of this NH_3 and has a massive carbon footprint, utilizing 1% of the world's total energy production and accounting for ~1.2% of global annual CO_2 emissions. The chemical reaction in this process is run at 500˚C and generates a molecule of CO_2 as a coproduct for every molecule of NH_3 synthesized, leading to ~2.8 tons of CO_2 emission for every ton of NH_3 produced. Thus, the extensive use of synthetic fertilizers in today's agriculture comes with severe environmental penalties, including a significant increase in the global carbon footprint. An alternative approach relies on biological conversion of nitrogen, a greener process restricted to only a few select groups of microbes. Of these, cyanobacteria can drive the energetically expensive reaction solely with solar power while simultaneously capturing CO_2, reducing the carbon footprint. Using non-model cyanobacteria as a chassis to convert atmospheric nitrogen into valuable N-rich compounds requires significant fundamental research activities. This project addresses basic research challenges to develop N_2-fixing cyanobacteria as cell factories to produce nitrogen-rich compounds. The work focuses on the production of guanidine, ammonia, and urea, three nitrogen rich compounds that can serve as substitutes for synthetic fertilizers. While ammonia is a rich source of nitrogen, the use of urea as a fertilizer is equally attractive and often surpasses the global use of anhydrous ammonia. Guanidine, on the other hand, is a slow-release nitrogen fertilizer. Unlike urea and ammonia which have an uptake efficiency of only ~50% by crop plants, leading to significant wastage, guanidium salts can ensure more controlled and protracted release of nitrogen and better utilization efficiency. The project involves two strains representing two contrasting paradigms that cyanobacteria use to accommodate the mutually antagonistic processes of oxygenic photosynthesis and nitrogen fixation: temporal separation in a unicell and spatial separation in a filament. The project will yield novel enzymes capable of catalyzing the conversion of N_2 into guanidine, ammonia, and urea as well as membrane transporters that will secrete the products out of the cell. Multiomics studies and machine learning tools will unravel the fundamental principles underlying the regulation of carbon and nitrogen fixation in cyanobacteria and their channelization towards the products of interest. This technology, when fully developed, has the potential to replace the use of synthetic fertilizers, and addresses the Carbon Negative and Industrial Heat Energy Earthshot goals of the Department of Energy. The team envisions future deployment of such strains in soil as a source of nitrogen and in ocean fertilization for CO_2 removal. Moreover, the fundamental knowledgebase developed could have a broader scientific impact on carbon neutral biomanufacturing of petrochemical replacement compounds and material. The project team brings together significant interdisciplinary expertise in cyanobacterial systems biology, computational modeling, AI, machine learning and synthetic biology. An important mission of this project is to train students and trainees from underprivileged communities. The project team is committed to fostering principles of diversity, equity, inclusion, and accessibility to create a research environment where all participants matter and belong.

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